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THESIS

DEVELOPING A DECISION SUPPORT TOOL FOR WASTE-TO-ENERGY CALCULATIONS USING ENERGY RETURN ON INVESTMENT

by

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December 2016

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Using systems engineering methodology, we build a decision support tool that enhances the Navy's ability to evaluate the economic viability of sites for waste-to-energy technologies, mirroring the current tool's capabilities and expanding its use. This tool returns recommendations about investing in waste-to-energy technology for a given facility or site. The recommendations are actionable results for the user in an easily digestible format in Microsoft Excel. The team has examined current Navy systems that evaluate waste-to-energy technologies and identified their shortfalls. These gaps directed the team's focus toward the critical areas that required improvement and/or development, including specifying required data and data sources. The team conducted stakeholder analysis and functional decomposition of the requisite model before constructing its additional module to the tool. This study shows the viability of waste-to-energy technologies to the Navy and Department of Defense. It supports the development of renewable power sources for a green Navy.

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Using systems engineering methodology, we build a decision support tool that enhances the Navy's ability to evaluate the economic viability of sites for waste-to-energy technologies, mirroring the current tool's capabilities and expanding its use. This tool returns recommendations about investing in waste-to-energy technology for a given facility or site. The recommendations are actionable results for the user in an easily digestible format in Microsoft Excel. The team has examined current Navy systems that evaluate waste-to-energy technologies and identified their shortfalls. These gaps directed the team's focus toward the critical areas that required improvement and/or development, including specifying required data and data sources. The team conducted stakeholder analysis and functional decomposition of the requisite model before constructing its additional module to the tool. This study shows the viability of waste-to-energy technologies to the Navy and Department of Defense. It supports the development of renewable power sources for a green Navy.

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LIST OF ACRONYMS AND ABBREVIATIONS

CEPCI	Chemical Engineering Plant Cost Index
CNIC	Commander, Navy Installation Command
DOD	Department of Defense
ECM	Energy Conservation Measure
EIA	Energy Information Administration
eROI	Energy Return on Investment
ESA	Environmental Services Association
FFBD	Functional Flow Block Diagram
GRN	Global Recycling Network
kW	Kilowatt
KWH	Kilowatt Hour
MOE	Measure of Effectiveness
MW	Mixed Waste
MWH	Megawatt Hour
NAWTEC	North American Waste-to-Energy Conference
ROI	Return on Investment
SSO	Source Separated Organics
SWANA	Solid Waste Association of North America
TPD	Tons Per Day
TPY	Tons Per Year
WM&R	Waste Management and Research
WTE	Waste-to-Energy

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EXECUTIVE SUMMARY

This study seeks to improve the Commander, Navy Installation Command (CNIC)'s existing Energy Return on Investment (eROI) decision support tool with an additional module, which may help increase the prevalence of waste-to-energy (WTE) technology within the Department of Defense (DOD).

The CNIC has developed the eROI tool, giving a measure of the project's maximized return on investment (ROI) value. The ROI is calculated from a sum of financial benefits that takes quantitative and qualitative measures into account (Brown 2015). The eROI computes the ratio of the ROI and the discounted capital expenditure for a given WTE project. A ratio that is greater than 1.0 implies that the project benefits exceed its cost, which supports an argument for the project to proceed.

Currently, the eROI allows users to input user-defined quantities to estimate the benefit-cost ratio. This estimate assumes two things: that the user completely understands those numbers required of him or her and that the types of numbers are all numerically comparable to each other and captured by these queries. However, WTE technologies require a variety of inputs and complicated methods to craft any estimations for facility costs. Major technologies that are mature enough to implement within the Navy include incinerators, plasma gasification, and anaerobic digesters. Yet, these technologies are not considered in eROI calculations and there is no guidance on what is required for their estimation.

This thesis studied the above WTE technologies and developed a spreadsheet module for inclusion in the eROI model. This spreadsheet uses a minimal amount of additional information about a potential project to produce three estimates, one for each type of WTE facility. The calculations for these estimates are based on scaling formulas found primarily in *Perry's Chemical Engineers' Handbook*.

Source:

Brown, Jim. 2015. *Web EROI Project Development User Manual*. CNIC Navy Shore Energy Program Development.

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I. INTRODUCTION

> When it comes to renewable energy, there's no reason America should settle for second best.
>
> —Senator Martin Heinrich (D-NM) (Wold 2010)

The U.S. Navy's Shore Readiness Division (N46) posed a question, asking what facilities are best suited to repurpose waste products toward power generation, and which technologies would be most appropriate for implementation at shore facilities. Providing some insight on this question, this study seeks to improve the Commander, Navy Installations Command (CNIC's) existing Energy Return on Investment (eROI) decision support tool by adding a module that may increase the diversity and breadth of Waste-to-Energy (WTE) technology within the Department of Defense (DOD). The eROI model currently calculates the economic benefit of new renewable energy projects based on construction, demand, current prices, growth, and service utilities. The planned additional module will allow a user to evaluate the viability of building one of several WTE facilities in the same location.

A. WTE BACKGROUND

WTE technologies take what we think of as "waste," such as sewage effluent or commercial trash service, and turn it into energy. For the Navy to select any WTE technology, it must produce more value than it costs and be a proven technology, competitive with current commercial operations. To compare WTE models, we must establish value metrics that are common between the models that also satisfy the sponsor's needs. We will first identify several technologies that fit our scope of research that are comparable, then define those common metrics. The technologies chosen represent three major methods of WTE processes currently used in the commercial environment: Incineration, Anaerobic Digestion, and Plasma Gasification. These three methods convert biomass to energy, which accounts for more than 50% of all renewable energy produced within the United States. (Energy Information Administration [EIA] 2016)

1. Incineration

A waste incineration system raises trash to a high enough temperature to cause combustion, producing hot gas and ash. The ash has a largely reduced volume compared to the input, making it an efficient way to extend the life of a landfill. The ash can be used as a product in some industries or sold to the local community as a construction material so long as it is non-hazardous, and if those are not viable options, it goes to the landfill (Environmental Services Association [ESA] 2016). Additionally, when the waste incinerated includes some metal products, some of the metal can be re-captured via recycling methods to be used as an additional source of revenue.

The gasses produced from combustion vary based on the trash that is burned, but a method of filtration for harmful products is required for this method. The gas can be run counter-current against the input trash, heating it up to reduce the required heat and residency time within the reactor. The gas can also be used to power a turbine-style engine, resulting in an energy product for the user.

In Figure 1, we see one example of this style of power plant. The incineration of trash can be environmentally harmful if not properly managed, as it results in effluent gasses that need to be scrubbed thoroughly to remove possible sulfur and nitrogen products that have negative impacts on the ozone and local air quality. According to AENews, the filters themselves then have to be disposed of as hazardous products or neutralized to make their storage acceptable (AENews 2016).

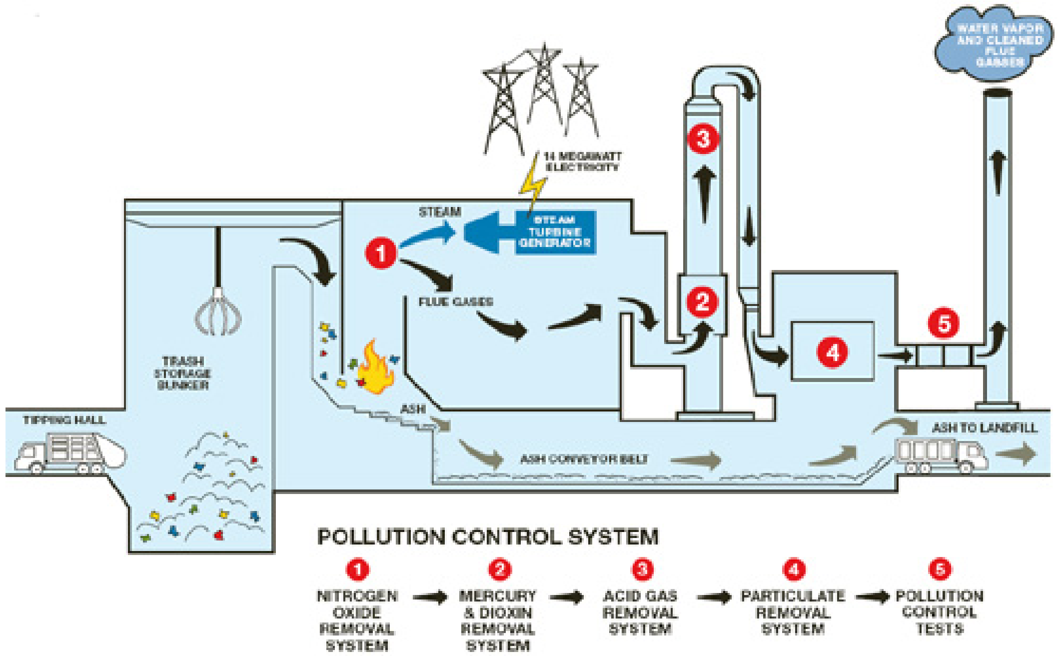

Figure 1. Incinerator with Cogeneration. Source: Taylor (2016).

2. Anaerobic Digestion

Anaerobic digestion uses a fermentation process to produce methane from organic waste inputs, resulting in a biogas that is then scrubbed (concentrated by removing contaminants) using a separation tower and either used directly as a product (biogas) or partially combusted to create higher-level hydrocarbons that can be used as fuels. Anaerobic digestion uses microbiomes that consume the waste and turn it into methane and carbon dioxide, the internal chemistry of the process described in Figure 2.

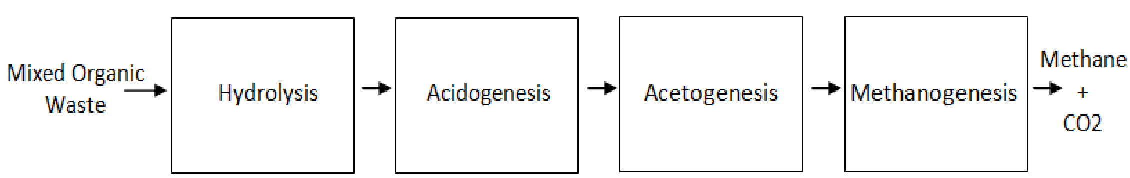

Figure 2. Digestion Process

The type of reaction tank and the environmental factors can greatly affect its efficiency of operation. However, it has a low energy input requirement for its conversion factor. An example of this style of WTE facility is shown in Figure 3.

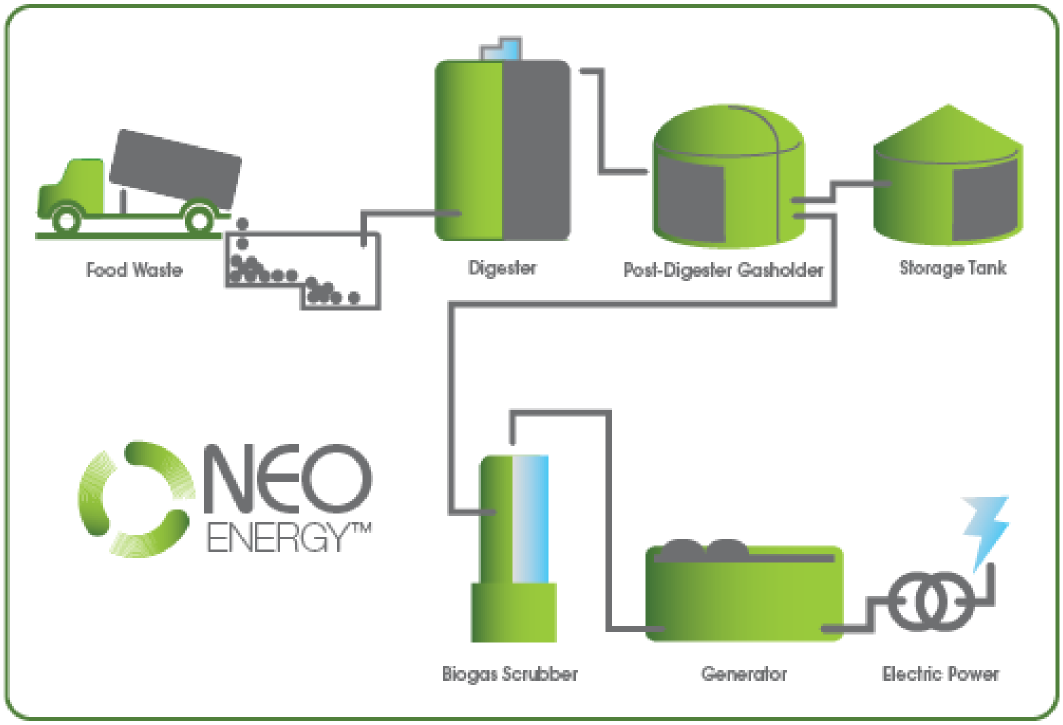

Figure 3. Anaerobic Digester Example. Source: NEO Energy (2016).

Anaerobic digestion is a mature technology, employed for energy production since the 1800s. Its effluent gas is used as an energy product, and its resulting "bottoms" (the solid product) can be used as an agricultural product or sent to a landfill as a reduced volume product. The process does not result in as large a reduction in volume as incineration unless the bottoms are incinerated, and the plant produces a noticeable smell in the immediate vicinity of the plant. The chemistry of the reaction tank also requires monitoring and a significant input of water depending on the type of waste input so that the microbiomes continue to be active.

3. Plasma Gasification

Plasma gasification refers to the use of an arcing electrical current on organic materials. In the reaction chamber waste rises to a much higher temperature than possible by simple combustion, creating an efficiently converted effluent gas stream plus a small solid waste stream. This gas (largely hydrogen and hydrocarbons) can then be used as synthetic gas (syngas) in place of traditional methane and burned for use in a biogas engine or further refined and stored as a fuel source. An additional benefit is that the instantaneous conversion does not allow the formation of sulfur and nitrogen containing oxygen products (SO_X and NO_X) meaning that this method produces fewer gasses requiring filtration than incineration. The solid waste stream is a slag, inorganic compounds that could not be converted to syngas that can exceed 99% purity depending on what was input into the machine. They are completely stable and inert and can be used in construction products or separated for further processing as metal products (HowStuffWorks 2016). Figure 4 shows one example of a plasma gasification facility in the same style as some commercial facilities in Japan.

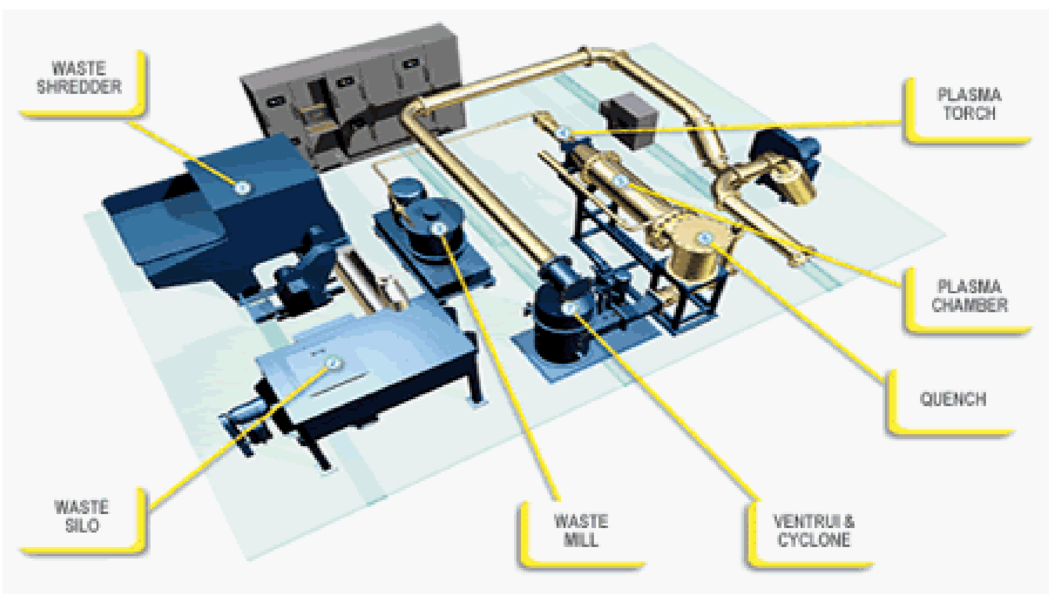

Figure 4. Plasma Gasification Process. Source: HowStuffWorks (2016).

Plasma gasification technology is the newest technology of these three choices, recently incorporated in the design for the Gerald R. Ford-class aircraft carrier (NEO Energy 2016). The disadvantages of this technology include the high initial cost, the risks associated with investing in a newer technology with complicated equipment, and a higher maintenance costs over alternatives.

4. Generalized Processes

These three types of WTE can be broken down into their common components for comparison. When thought of as a function of requisite inputs versus expected outputs and values added to each variable, we can imagine a model that is comparable to other models based on a cost-benefit basis. Each variable could provide value and/or cost, no matter the inner machinations of the system itself. If the user is then provided these estimate numbers, they would be better informed of the economic impact if built before investing in a more complicated model. With this in mind, it is then useful to examine the current tool in use by the DOD to see if improvements or modifications would be adequate to provide users with enough information to make a decision about a WTE facility. Figure 5 is the generalized process model that will assist with further development of a formal economic model for WTE within eROI.

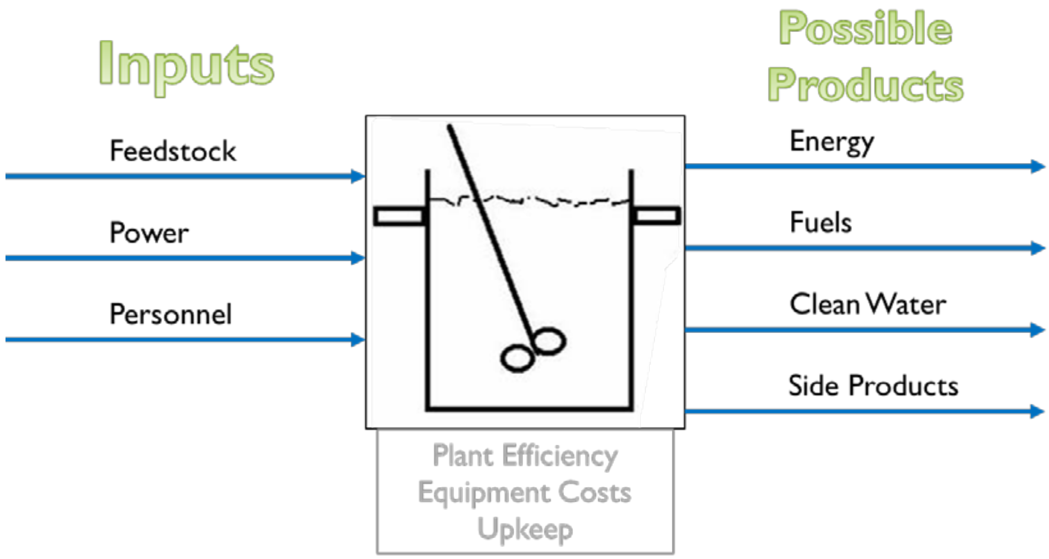

Figure 5. Simplified Input-Output Model.

B. THE ENERGY RETURN ON INVESTMENT (EROI) TOOL

The eROI tool is managed by CNIC, serving as a versatile model that estimates the costs and benefits of energy-related construction projects. The tool uses complex spreadsheets with generic data columns that take user inputs and return a calculation based on user-defined local price information, the final result being the "eROI number." Figure 6 is the primary user interface for the tool. The intent of eROI is to inform decision makers on how to invest in financially beneficial technologies. A primary goal is for the Navy to have a dependable and repeatable process based on research and fact.

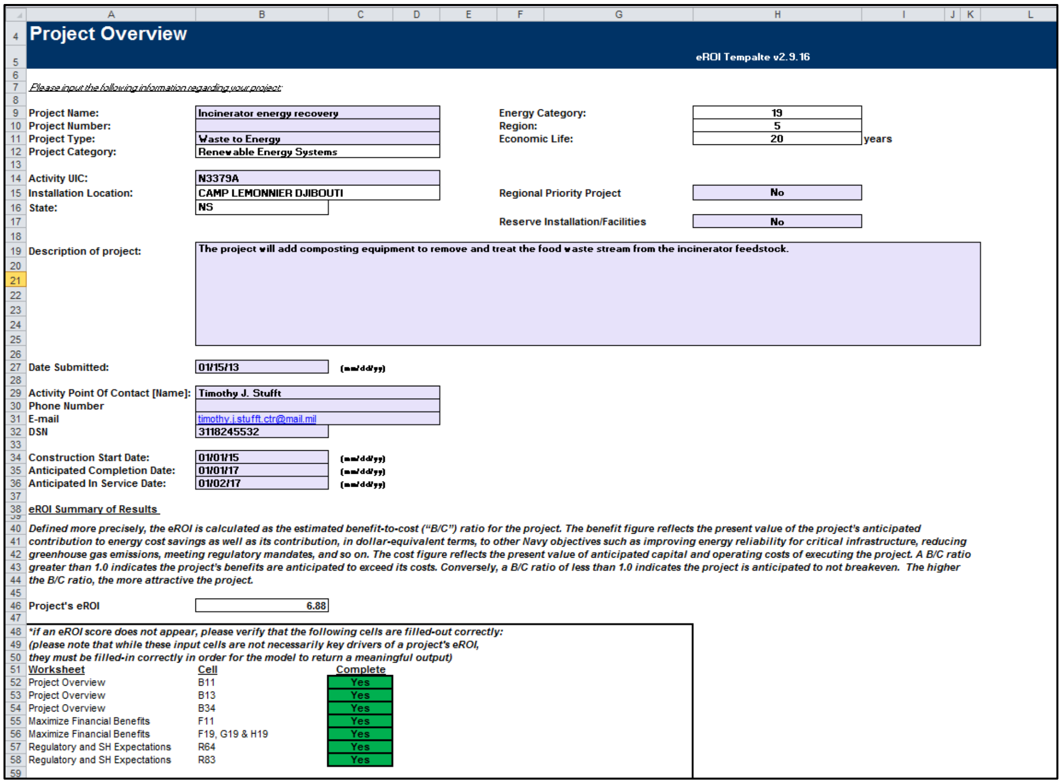

Figure 6. Primary User Interface for eROI.

The eROI spreadsheet model accepts information from Energy Conservation Measures (ECMs) via a separate template and breaks the information into 51 relevant columns, which are fed into different calculations within the model (Brown 2015). Additional information for the project is entered, including project number, reason, cost planning/analysis, and construction dates. The model automatically determines whether or not it requires additional information. It computes whether the cost to benefit ratio is positive, a litmus test for the project's viability to the navy. This resultant ratio is referred to as the "eROI number" of the project, a number our model will also calculate.

The current model puts weights on different categories of information, putting the most emphasis on cost savings / avoidance and the addition of reliable energy to critical infrastructure (together accounting for 65% of the total score), while placing lesser emphasis on environmental considerations, meeting regulatory mandates, and "developing flexible energy infrastructure." These are important intangibles that are useful, but based less on mathematics and more on the opinions and perceptions of the project. Using eROI as an analytical aid, it can become clearer to decision makers which projects are feasible and remove those that do not need to be investigated further. If this thesis will potentially add value to the eROI model, it is important to see where it fits into the process through a context diagram to better scope additional functionality requirements.

C. THE PROBLEM AT HAND

Our sponsor posed two research questions for this study: 1) How do we determine which facilities have the resources to implement WTE technology? 2) What type of technology should we implement? The method to conduct this analysis would be to compare similar technologies based on their economic predictions, picking a model that provides a positive cost-to-benefit ratio. The problem that the typical eROI user has is not whether or not it is profitable or useful to perform an analysis, but where to begin. Therefore, providing the user with a starting point will be one of this project's primary goals. This thesis will consider how the existing eROI decision support tool can be improved with an additional module that will evaluate the viability of WTE technology. To develop this module, it is important to examine that research which has already been conducted and review appropriate literary sources on the subject matter.

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II. LITERATURE REVIEW

To get a useful cost estimate, original sources of cost estimation were examined for each type of WTE technology and those numbers correlated using formulas found in *Perry's Chemical Engineers' Handbook*, hereafter referred to as *Perry's*. The original sources used were from *Biocycle* magazine, the American Society of Mechanical Engineering, and the Waste Management and Research Group. Past work relevant to this topic has also been completed by the DOW Chemical Company, the American Institute of Chemical Engineers, and various other research groups. All of these sources played a role in crafting a new tool for eROI users.

A. PAST WORK

There has been no direct past work conducted to modify eROI and add a module that would perform the functions requested by N46. There have been studies that correlated cost estimation models with different plant types, but no specific work for eROI in this line. We will be using chemical engineering theory from *Perry's Chemical Engineers' Handbook* coupled with studies conducted on operational plants to create an estimate of actual cost and production data (Perry 2008).

B. PERRY'S CHEMICAL ENGINEERS' HANDBOOK

Perry's has been a source for chemical engineers in their calculation work since John H. Perry penned the first edition in 1934 (Perry 2008). The book itself covers topics from foundational mathematics to the most recent process safety requirements in place. The chapter primarily used in this thesis was section 9, "Process Economics."

Within section 9 is the subsection "Capital Cost Estimation." It is here that we find a discussion of the most significant factors to consider when estimating the cost of any investments pertaining to the planned facility. This information will also make it clear what type of facility we should construct based on our data. From this, we see that with knowledge of our major equipment and the material balances (things flowing in and out of the plant), we can achieve a reasonable estimate of the cost (Perry 2008). *Perry's* collected and plotted the cost data for a multitude of plants and equipment versus their capacity, which resulted in the discovery of the six-tenths rule as shown by Figure 7.

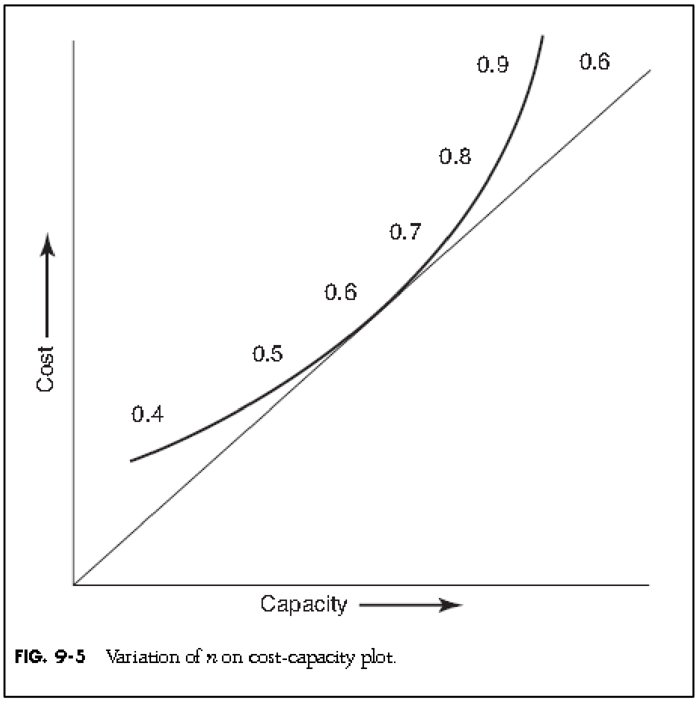

Figure 7. The Six-Tenths Rule. Source: Perry (2008).

The six-tenths rule states $C_{E,2} = C_{E,1}\left(\frac{S_2}{S_1}\right)^{.6}$, where C_E and S refer to the equipment cost and processing capacity respectively of plants 1 and 2. The level of error incurred by using this formula is acceptable for the scope of our estimation per a discussion with the sponsor. In similar line, when examining total capital costs of plants using the same process it was observed that they varied closely with their capacities, that is $C_{C,2} = C_{C,1}\left(\frac{S_2}{S_1}\right)^{.7}$ where C_C refers to the total capital cost of each plant and S refers to the processing capacity of the plants. This is known as the seven-tenths rule (Perry 2008). To ensure that equivalent dollars are being compared, we must adjust each number per its annual cost factor. While these rules will assist us in our calculations, it is important to have real-world data as well to base our cost estimation efforts on.

C. STUDIES FOR CORRELATION

For our investigation, we use four separate studies. The first study is about anaerobic digestion and thoroughly details a strategy for cost estimation based on input type and amount (Whyte 2001). The second study was an assessment for installing a plasma gasification plant in Florida, which was a metastudy of sorts that created a generalizable cost estimation formula for energy plants of the same type (Clark 2014). The third (Athanasiou 2015) and fourth (Tang 2012) studies were done on incineration units and included methods to calculate capital costs, fees, and benefits from the same.

1. Anaerobic Digestion Costs

This Biocycle article, "A Rough Guide to Anaerobic Digestion Costs and MSW Diversion," details the efforts of a senior consulting team within the Enviros RIS, an environmental consulting firm that specializes in waste and energy management issues (Global Recycling Network [GRN] 2016). It gives a range of estimated capital and annual costs depending on tons input for 10,000 to 100,000 tons per year (TPY) and types of waste as either source-separated organics (SSO) or as mixed waste (MW). Table 1 was adapted from the data in this article to make a correlation of values simpler to digest for our potential product.

Table 1. Anaerobic Digestion Estimation Factors. Adapted from GRN (2016).

	min	max
Range (tpy)	10,000	100,000
SSO Capital ($/tpy)	$625	$245
MW Capital ($/tpy)	$690	$265
Net Annual Cost SSO ($/tpy)	$107	$46
Net Annual Cost MW ($/tpy)	$135	$63

This article also provides an estimate for the value of the digestate produced (values range from \$1 to \$5; the reference suggests using \$2 is a safe estimation) and that 55% methane biogas is produced at a rate of 115(SSO) and 95(MW) m^3 per ton design capacity. Finally, we note that this paper's publish date was OCT 2001, meaning we must cost adjust all prices for use in our model.

2. Economic Feasibility of Plasma Arc Gasification

The North American Waste-to-Energy Conference (NAWTEC) is a yearly meeting of professionals who work within the solid waste management community. The group that hosts this conference is the Solid Waste Association of North America (SWANA), which was established in 1961 as a local governmental program. This article, "Economic Feasibility of a Plasma Arc Gasification Plant, City Of Marion, Iowa" was a study developed for evaluating a proposed plasma gasification project in Iowa, but its final product was generalizable for projects to build the same industry elsewhere. The study specifically looked at plants with capacities ranging 150 to 600 tons per day (TPD) and gives availability data for the plant, as well as a cost/benefit estimation based on capacity. Table 2 is a summary of some of the useful values from this article. This paper was published in 2010 and as such needs to be cost-adjusted for present day values.

Table 2. Plasma Gasification Variables. Source: Clark (2016).

Model Parameters	Assumption	Comment
Base Year	2014	Assumed
Planning Period	2014 – 2034	Assumed
Waste Flow Growth	2% Per Year	Assumed
Consumer Price Index	2.0%	Assumed
Interest Earnings (Of System Revenues)	2.0%	Assumed
Debt Financing Rate	8.0%	Assumed
Debt Service Coverage	125%	Assumed
Length of Bond Issue	20 years	Assumed
Treasury Grant Program	30 % of Capital Costs	U.S. Department of the Treasury
Landfill Tipping Fee (2009)	$35.00 per ton	Cedar Rapids, Linn County Landfill Tipping Fee
Availability of New Unit	75% Years 1 and 2 85% Years 3- 20	SCS Estimate
Slag to Aggregate Revenues	350 pounds per ton of waste processed; $0.52 per ton	SCS Estimate
Recovered Metals Revenues MRF Operations Plasma Arc Facility	3% of incoming waste (2.4% scrap ferrous, 0.6% aluminum cans) $300/ton for scrap ferrous, $0.82 per pound for aluminum cans 1.2 pounds per ton processed; $0.12 per ton	SCS Estimate
Renewable Energy Credit (REC)	$1.00 per megawatt hour (MWh)	SCS Estimate
Carbon Credit	2.2 tons of CO_2 per ton of processed waste; $7 per ton of CO_2	SCS Estimate, when comparing plasma arc against current landfill disposal method

3. Feasibility Analysis of Solid Waste Mass Burn

Waste Management and Research (WM&R) is a journal focused on sustainable waste management practices and other topics that pertain to WTE technology. This specific paper, “Feasibility Analysis of Municipal Solid Waste Mass Burning in the Region of East Macedonia—Thrace in Greece,” focuses on a feasibility study that provides helpful formulas for quick calculations including the energy produced by combustion of mixed waste types, and capital and operating costing formulas (using a formula similar to the seven-tenths rule). Additionally, it provides the process start to finish for conducting a feasibility planning effort, which was helpful when determining what numbers specifically had to be calculated versus what numbers could be reasonably estimated.

4. Cost-Benefit Analysis of Waste Incineration

The fourth article reviewed, "A Cost-Benefit Analysis of Waste Incineration with Advanced Bottom Ash Separation Technology for a Chinese Municipality—Guanghan" was a master's thesis from the Vienna School for International Studies (Tang 2012). The researcher compared large amounts of real-world data to get cost and benefit data for incinerator units that was more generalizable. This study helped correlate the plot data and check for accuracy in measurement versus real world data and provided some numbers for the capital cost estimation of incineration units.

D. THE EROI HANDBOOK

CNIC's Navy Shore Energy Program Development published, along with the eROI tool, a *Project Development User Manual* that thoroughly covers each section of the eROI tool and how to parse a project into it. It explains the end result of the eROI number, and goes through calculations in its appendices to ensure the user has a basis to defend results. When completed, the work done in this thesis was added in an appendix to the handbook to explain what the module calculated and how each calculation worked and included a list of references.

III. SYSTEMS ENGINEERING METHODOLOGY

Systems engineering is the process of engineering human-made systems through a methodical means to ultimately end up with a better process than what was began with. There are multiple methods to accomplish this process, from the standard V-models to complex waterfall methods, but ultimately each description of a system is a unique aid in the understanding and furthering of that which it models. By creating an encompassing model for our WTE system, we can ensure that our model is created via a logical and traceable process.

A. CONTEXT DIAGRAM / BOUNDARY ANALYSIS

To better understand the environment where our potential solution must operate, it is prudent to examine the boundaries of the system and any constraints or requirements imposed by interfaces with external systems. One tool that is useful in doing this is the External Systems Diagram, seeking to capture the flow of interactions between outside systems and the primary system of interest. Figure 8 allows a general look at the physical, functional, and behavioral boundaries between each functional group.

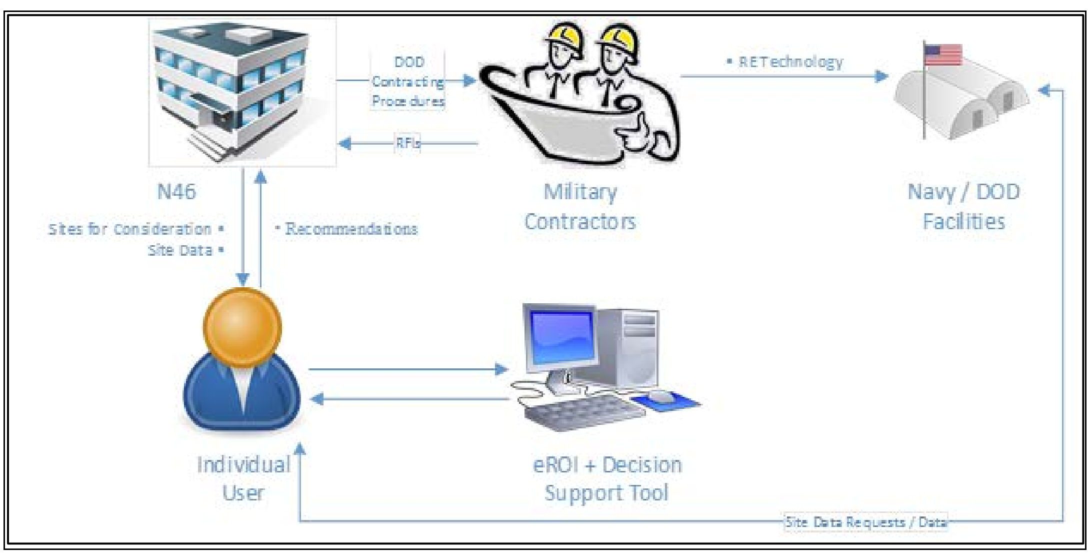

Figure 8. Decision Support Tool Context Diagram.

We can see that eROI's only interface is with the user, based on the diagram. Interactions with the model will be to retrieve user input, and interactions with the user will be to garner additional information in a simple and easily understood format. One concern is error reduction of a user's input; automation helps reduce errors of repetitive tasks such as updating tables and constants that the model relies upon. With the interactions thus explored, we now can generate a set of requirements that our model must meet to be an effective and useful tool from which to glean information for decision-making.

B. DEVELOPING SYSTEM REQUIREMENTS

The system requirements are a set of elements that are essential to the construction of a successful system, describing the functions that a system must perform to accomplish its intended purpose (Blanchard 2011, 61). Defining these elements is crucial at the start of system design, as they drive the design process and allow a way to ensure that no extraneous or incorrect elements are added to the system. The required functions are defined by the needs of the user who will be interacting with the system, and described in the following sections. As such, a brief stakeholder analysis should be conducted to ensure that all needs are addressed. After this, functional analysis maps out how the module will work before we define the system's requirements and ensure that the product will fulfill them.

1. Stakeholder Analysis

Any party or person who has an interest in the development of this tool, whether direct or indirect, can be viewed as a stakeholder. With systems engineering, the second most important process is defining the problem, and problem definition is based on the needs of all stakeholders involved. Our problem statement is "How can we improve the existing eROI decision support tool with an additional module that will evaluate the viability of WTE technology."

Table 3 identifies all stakeholders and describes each of their interests in the project. The table ranks each party by priority, from first to last. The "primitive needs" column shows each stakeholder's primitive need, while the next two columns expand to give effective needs and some concerns the stakeholder might have.

Table 3. Stakeholder Analysis.

Priority	Stakeholder	Type	Primitive Needs	Objective / Effective Needs	Concerns
1	Individual User	Direct User	Tool that is simple, effective, clear about required inputs	• Tool follows eROI existing format • Tool is clear about required inputs • Tool can operate without all possible inputs and will delineate which apply to different models • Tool gives an economic analysis that allows comparison to other project • Tool calculates the eROI number	• Goodness of fit (is the model accurate?) • Ease of use (is the model clear about requirements?) • Time input (does the model require too much information?) • Implementation (does the model fit into the already-accepted timeline?)
2	N46	Sponsor/Client	Proper cost-comparing assessment for decisionmaking	• Estimate provides actionable information • Resources exist for further assessments • Method to answer is properly documented	• Goodness of fit (is the model accurate?) • Further investigation (will the path forward be clear to the user?)
3	Military Contractors	Sponsor/Client	A decision for either further research or a go-ahead project	• Cost estimate • Budget • Clear path forward	• Funding • Clear project goals/deadlines
4	US Navy / DOD Facilities	Sponsor/Client	A project to move forward on	• User-friendly control interface • Clearly defined mission objectives • "Green" Project • Accurate results	• Timelines • Funding sources

The most important stakeholder is the user, as the module being developed has the primary purpose of giving useful information in an easily understood format to them. Secondary is N46, the organization who requested that such a module be developed, and tertiary are the contractors and Navy Organization as a whole as they will potentially be acting on the information that the user has produced. From this stakeholder analysis and our knowledge of the shortcomings of the current tool available to the user, we can now identify the functions that our additional module must encompass.

2. Functional Analysis

The functional analysis of a system gives a detailed analysis of what the system must do to meet the stakeholders' effective needs. The hierarchy outlined in Figure 9 begins at the highest level of the system (the additional eROI module overall), and breaks down into lower level functions while remaining broad enough for multiple solutions in terms of the overall scope of the project. The lines connecting each child function to its parent show similarities, such that all child functions under one branch are a family (relate to the same functionality).

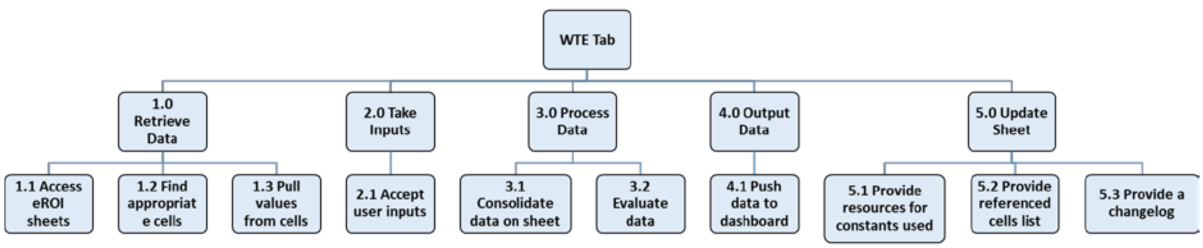

Figure 9. Functional Hierarchy.

While the Functional Hierarchy is a useful tool for breaking down higher-level system functions and sub-functions required of the system, it does not adequately display these sub-functions in a logically sequential manner. Creating a System Functional List, as done in Table 4, gives clarification to each sub-function and allows for the creation of a basic Functional Flow Block Diagram (FFBD).

Table 4. System Functional List.

Level	Function	Description
1.0	**Retrieve Data**	**The sequential gathering of data from other eROI tabs that fills reference cells within the data sheet.**
1.1	Access eROI Sheets	Properly reference and access data on different eROI sheets
1.2	Find Appropriate Cells	Find the correct data on the correct spreadsheet, even if the cells were switched or moved
1.3	Pull values from cells	Bring data from other sheets to a local cell block
2.0	**Take Inputs**	**The direct user inputs.**
2.1	Accept user inputs	Allows user input, notifies user if input is wrong or missing, including values that appear to be out of a "normal" range.
3.0	**Process Data**	**The evaluation of collected data with a goal of creating a comparable number.**
3.1	Pull data from sheet	Reference appropriate sections of cell block (1.3) and detail any that are missing
3.2	Evaluate data	Use appropriate formulas and inputs to give an output estimation where enough data exists, and an indication that it does not exist when there is insufficient data.
4.0	**Output data**	**The display of the results of data processing to the user**
4.1	Push data to dashboard	Display the user-created data on a visible "dashboard" for the user.
5.0	**Update**	**The update of the WTE tab to ensure that cells and sheets are appropriately referenced.**
5.1	Provide resources for constants	Give the potential user the location of all "constants" to ensure accuracy
5.2	Provide referenced cells list	Give the program maintainer a list of all referenced cells so that if updates are made to other sheets the integrity of the sheet is maintained.
5.3	Provide changelog	Provide the program maintainer a change log to ensure that updates are properly addressed.

3. Functional Flow Block Diagram

The basic functional flow block diagram shown in Figure 10 details how each function included within the module interconnects, which shows a clear traceable path of how the module allows it to come to its solution. For our model, the FFBD is straightforward.

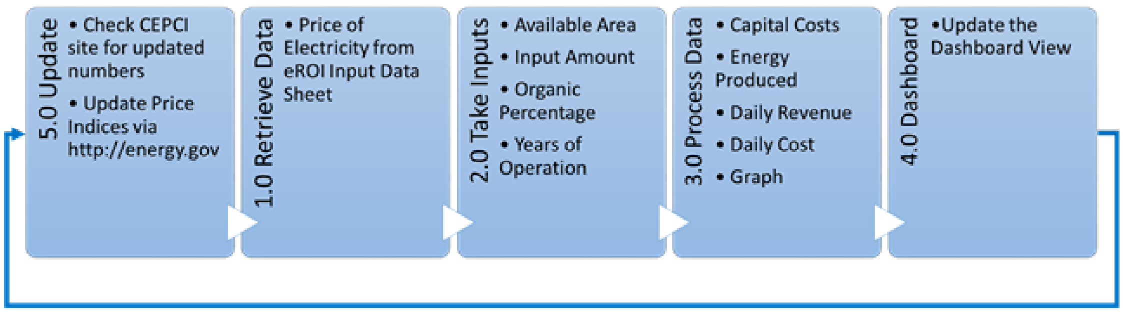

Figure 10. Basic Functional Breakdown

Before calculation, the system will update numbers for price indexes in 5.0 so that the model has accurate information before running. Next in 1.0 the price of electricity is referenced from earlier entries into the spreadsheet, which plays a large role in calculating whether or not a process is profitable. In 2.0, the user inputs the appropriate researched values that are then evaluated in 3.0 to update the final products and graph, then pushed to the dashboard view in 4.0.

4. Functional Architecture

The functional architecture of our system describes it in terms that we can attribute functions to each element. It connects our system through the top-down style of describing functions, operational interfaces, scenarios, and their environment. At its most basic level, it is a description of how we will get to a solution from the needs that we have detailed.

The system as described can be fulfilled by modifying the existing eROI model to add a spreadsheet that takes user inputs through specified input areas, pulls data from existing portions of the sheets, and calculates a resultant for the user. It can fulfill all requirements through this method while keeping within the existing structure, as well as adding value to the existing system and additional functionality. It can also be updateable with a low amount of user research via Excel-based macros.

C. REQUIREMENTS

The requirements for the system are the elements that it must include. They are the basis of the solution to the problem statement. The requirements follow the functional analysis of what our system must do in order to accomplish stakeholder objectives.

a. The Module Shall Include a Numerical and Visual Way to View the Results

The module shall have at least two ways for the user to view its results, preferably in similar format to the rest of the eROI model. This will ensure that all information can be understood without introducing the user to a new, unfamiliar format that could lead them to misinterpret the results. This may be accomplished by having a "dashboard" view, a simplified area close to where the user inputs their information so that they do not have to scroll or search for information.

b. The Module Shall Only Require Information Obtainable at No Additional Cost to the User

This tool is designed to be user friendly and simple such that it can provide a rudimentary estimate with as little additional user time spent on it as possible. If the model requires too many inputs or those inputs require funding, the likelihood of it being completed or completed correctly sharply decrease and it becomes less useful.

c. The Module Shall Be Intuitive or Provide Guidelines for User Interaction

Without appropriate guidance at every step, the chance of a user inputting incorrect information or correct information in an incorrect area is increased. An addition to the existing eROI instruction manual must be included, and the presence of guidance in each user entry area increases the reliability of the tool.

d. The Module Shall Provide Any Resources Required for Updates to the User

When dealing with a model that gives a cost estimate based on present and future dollars, the model must be able to retrieve the appropriate price indices or it loses its relevancy quickly. To reduce the strain of research on the user, a way for updating the model must either be automated or have clear and concise instructions provided such that there is low risk for error.

e. The Module Will Only Provide a Preliminary Estimate, and This Must Be Made Evident to the User

The formulas used in the development of this model provides the user with a rough cost/benefit estimate of each technology's cost and value. The process of the estimate is transparent to the user in the additional literature provided.

D. ALLOCATING FUNCTIONS TO REQUIREMENTS

To verify that all requirements have been met, they have been matched to their applicable functions as shown by Table 5.

We see that all requirements are verified as covered by the model, but the model also needs to be validated as functioning properly. In order to validate the model, its product (the calculated costs and values) must be tested against real world data. This thesis sought to conduct type 3 and type 4 testing but was unable to obtain adequate data to test the model against. The sponsor was consulted and has agreed to conduct this testing. The goodness of fit of the model can be calculated by graphing the difference between hypothetical and actual and this error categorized as systematic (where some part of the formula is wrong) or random (where the model or data are inadequate for this model). All requirements are met by our choice to create a module within the existing eROI model, so we proceed with the model development and creation.

Table 5. Functional Allocation for Requirements.

Level	Function	Requirement a	Requirement b	Requirement c	Requirement d	Requirement e
1	**Retrieve Data**	**X**				
1.1	Access eROI Sheets	**X**				
1.2	Find Appropriate Cells	**X**				
1.3	Pull values from cells	**X**				
2	**Take Inputs**	**X**	**X**	**X**		
2.1	Accept user inputs	**X**	**X**	**X**		
3	**Process Data**					**X**
3.1	Pull data from sheet					**X**
3.2	Evaluate data					**X**
4	**Output data**	**X**				**X**
4.1	Push data to dashboard	**X**				**X**
5	**Update**	**X**	**X**	**X**	**X**	
5.1	Provide resources for constants	**X**	**X**	**X**	**X**	
5.2	Provide referenced cells list	**X**	**X**	**X**	**X**	
5.3	Provide changelog	**X**	**X**	**X**	**X**	

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IV. MODEL DEVELOPMENT

Having chosen to create a module for eROI, we examine the environment in which to build it. Microsoft Excel is a highly flexible program that is used throughout the military. It does not requiring any additional installations for users or downloads other than the standard Microsoft Office suite already present on most DOD PCs . In addition, by building the module within an existing model, we ensure that distribution will occur directly to personnel who would already be making these considerations. The next important step is looking at what specifically needs to be included within our model for it to be functionally sound before we start considering formulas needed for each cell.

A. MODEL DESIGN

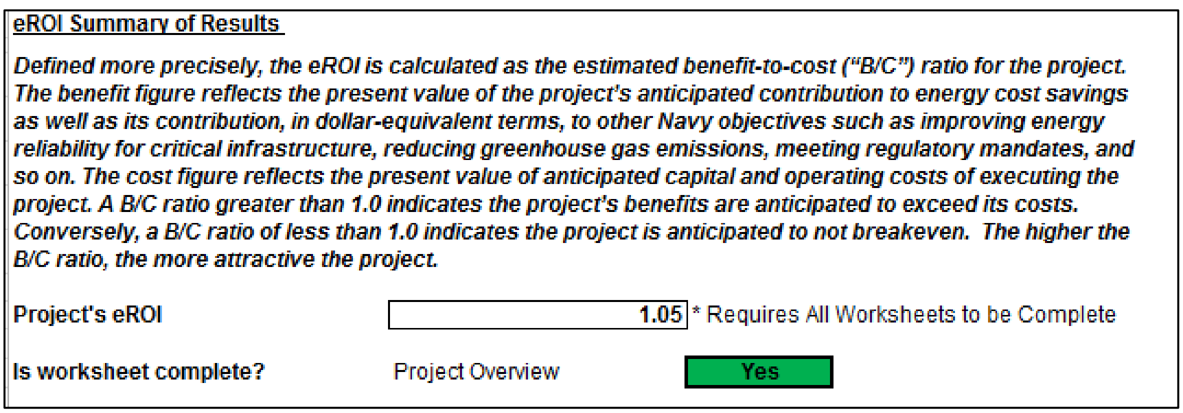
The end purpose of the model is to provide additional information to the user about WTE technologies that could fit the needs of a military installation. To that end, there are four measures of effectiveness (MOEs) for WTE technologies that help us determine its appropriateness for the facility: Capital Cost, Availability, Reliability, and Sustainability.

Capital Cost refers to the up-front costs associated with building the new technology. Without appropriate input of funding the technology cannot be built. Availability refers to the ability of the technology to physically be constructed in the location. If there is not enough room or an ideal location then the technology cannot be expected to succeed. Reliability refers to the expected lifetime of the technology and maintenance required. Longer lifespans and reduced maintenance costs are important to keeping a facility profitable. Sustainability refers to the facility's ability to be provided for by the local resources available to it.

Based on the requirements set forth: Sustainability is the most important metric as it specifically is addressed by the problem statement. Reliability and Capital Cost are equally important as they drive whether or not building the technology is a financially sound decision. Availability is least important though worth consideration due to the military’s supply network. The only metric that this module will seek to calculate is Sustainability, the other three metrics should be taken into consideration by the user as non-numerical factors when choosing whether or not to invest in the technology.

B. MODEL CONSTRUCTION

Keeping the MOEs in mind, the current eROI model was examined for both style and function. The result is an “eROI number” that is a benefit-to-cost ratio which includes several factors that require the user to make a judgment call about the project. If this results in an eROI number that is greater than one, then the proposed energy technology has merit for further research and investigation. If the number is less than one but meets certain requirements, it could merit further investigation due to providing some other necessary benefit that the military deems worth the cost, or perhaps a benefit that was not examined by the study. The current eROI summary that users see is shown in Figure 11. Otherwise, the eROI sheet is meant to assist in removing undesirable projects before significant resources are allocated toward them.


eROI Summary of Results

Defined more precisely, the eROI is calculated as the estimated benefit-to-cost (“B/C”) ratio for the project. The benefit figure reflects the present value of the project's anticipated contribution to energy cost savings as well as its contribution, in dollar-equivalent terms, to other Navy objectives such as improving energy reliability for critical infrastructure, reducing greenhouse gas emissions, meeting regulatory mandates, and so on. The cost figure reflects the present value of anticipated capital and operating costs of executing the project. A B/C ratio greater than 1.0 indicates the project's benefits are anticipated to exceed its costs. Conversely, a B/C ratio of less than 1.0 indicates the project is anticipated to not breakeven. The higher the B/C ratio, the more attractive the project.

Project's eROI 1.05 * Requires All Worksheets to be Complete

Is worksheet complete? Project Overview Yes

Figure 11. eROI Number Calculation.

As a comparison for this process, an eROI number should be the result of the additional module to simplify user analysis of the eROI model. This number would additionally be a concise way to compare the results of the three selected WTE technologies against one another on a dashboard view, displaying to the potential user costs, benefits, and the viability of a feasible energy project. To calculate the three eROI numbers, each WTE technology has a different set of calculations and cost/benefit balances that need to be detailed properly. The Chemical Engineering Plant Cost Index (CEPCI) will be used to adjust numbers from different years to be current-year equivalent for all capital costs.

1. Anaerobic Digestion Calculations

For Anaerobic Digestion, the seven-tenths rule from Perry's (Perry 2008) and the sample study from *Biocycle* (GRN 2016) magazine were used. A plant estimated at 34 tons/day processing power and a CEPCI of 100 was valued at $8.5 million. The capital cost formula was then applied using the ratio of user input tons/day of material versus the sample plant and then adjusted via the current CEPCI. Costs per year were assumed at 10% of the capital costs (Perry 2008). The revenue is a summation of the digestate and electricity produced, both of which are dependent on the percentage of organic materials that comprise the input waste. The digestate can be reasonably estimated to have a value of $60 per ton. Methane content of biogas can vary, but normally comprises approximately 55% by volume of the resultant gas. This lower methane content results in the biogas producing energy at approximately 6 kwh per cubic meter of methane, with expected engine efficiency of .4 when using combined heat and power engines (Perry 2008).

$$Capital\ Cost = Example\ Plant\ Cost * \left(\frac{Est.Capacity}{Example\ capacity}\right)^{.7} * \left(\frac{CEPCI_{current}}{CEPCI_{example}}\right) \qquad Eq.\ 1$$

$$Operation\ Cost(life) = \frac{Cost}{day} * 365 * availability * years \qquad Eq.\ 2$$

$$\frac{Cost}{day} = \frac{.1 * Capital\ Cost}{365 * availability} \qquad Eq.\ 3$$

$$Value(life) = \frac{Revenue}{day} * 365 * availability * years \qquad Eq.\ 4$$

$$\frac{Revenue}{day} = \left(E_{prod} * P_E\right) + \left(Digest_{prod} * P_D\right) + \left(Fee_{tip} * W_{waste}\right) + \left(RECs * E_{prod}\right) \qquad Eq.\ 5$$

$$E_{prod} = \left[\left(115 * Wt\%_{Organic}\right) + \left(95 * Wt\%_{Inorganic}\right)\right] m^3 biogas * \frac{\left(6 * 10^{-3}\ MWH\right)}{m^3 biogas} \qquad Eq.\ 6$$

Where E_{prod} is the energy produced (MWH), P_E is the price of energy $\left(\frac{\$}{MWH}\right)$, $Digest_{prod}$ is the amount of digestate produced $\left(\frac{tons}{day}\right)$, P_D is the price of the digestate $\left(\frac{\$}{ton}\right)$, Fee_{tip} is the price per "tip" of a garbage truck $\left(\frac{\$}{ton}\right)$, W_{waste} is the weight of incoming waste (tons), and *RECs* are renewable energy credits given to renewable energy producers that have a value $\left(\frac{\$}{MWH}\right)$.

2. Plasma Gasification Calculations

Plasma gasification will take input waste of any mixture and turn it into Syngas, a flammable mixture of methane and other combustible gasses typically burned for electricity, and slag, a mixture of ash and inorganic materials that are processed to obtain purified components or landfilled. Estimation via equipment scale-up was conducted to calculate the capital cost of the plant. The tons per day of input waste was multiplied by $220,000, the average dollar cost per ton for a basic mass-burn plant equipment setup. This number was then scaled back by 25% to account for equipment that is covered by specific large pieces of equipment for estimation purposes (Clark 2016). Other basic equipment costs are added, including the scale house cost (where the waste enters the plant), the utility interconnections cost, the waste pre-processing (where the waste is shredded as much as possible), the plasma arc furnace itself, and the heat exchanger that keeps the reaction vessel, where the conversion happens, at an appropriate temperature. All of this produces a total capital cost, which is adjusted to current year dollars.

The energy produced is estimated at 533 kW per ton of waste input, though the actual amount will vary, largely based on the types of input waste and other factors. Table 2 shows that slag can be reasonably estimated at 350 lbs. per ton processed, and that the slag can be valued at approximately the price of the metals contained therein, $228 per ton processed. Additional revenue comes from the local tipping fee (averaged at $35/ton, entirely location dependent) and Renewable Energy Credits from the government (volatile market, very low estimate of $1/MWH produced via renewable sources).

The Operation and Maintenance cost of a plasma gasification plant can be estimated to be approximately 10% of its capital cost per year based on the model presented in the NAWTEC article (Clark 2016).

$$Capital\ Cost = \left[\left(\frac{\$220{,}000}{ton\ waste}\right) * (W_{waste}) * .75 - \$1{,}200{,}000\right] + Cost_{equipment} \qquad Eq.\ 7$$

$$Operation\ Cost(life) = \frac{Cost}{day} * 365 * availability * years \qquad Eq.\ 8$$

$$\frac{Cost}{day} = \frac{.1 * Capital\ Cost}{365 * availability} \qquad Eq.\ 9$$

$$Value(life) = \frac{Revenue}{day} * 365 * availability * years \qquad Eq.\ 10$$

$$\frac{Revenue}{day} = \left(E_{prod} * P_E\right) + \left(Slag_{prod} * P_S\right) + \left(Fee_{tip} * W_{waste}\right) + \left(RECs * E_{prod}\right) \qquad Eq.\ 11$$

$$E_{prod} = \frac{533\ kwh}{ton\ waste} * W_{waste} \qquad Eq.\ 12$$

Where E_{prod} is the energy produced (MWH), P_E is the price of energy $\left(\frac{\$}{MWH}\right)$, $Slag_{prod}$ is the amount of slag produced $\left(\frac{tons}{day}\right)$, P_S is the price of the slag $\left(\frac{\$}{ton}\right)$, Fee_{tip} is the price per "tip" of a garbage truck $\left(\frac{\$}{ton}\right)$, W_{waste} is the weight of incoming waste (tons), and *RECs* are renewable energy credits given to renewable energy producers that have a value $\left(\frac{\$}{MWH}\right)$.

3. Incinerator Calculations

Incinerators are some of the oldest and most basic WTE technology, and as such are well understood for cost estimation purposes. A standard mass-energy burn plant can be estimated at $220,000 times the input tons per day for capital costs (Clark 2016). Additionally, taking into consideration losses due to efficiency and parasitic electricity costs the average amount of electricity produced is 200 KWH per ton of waste burned daily. The process reduces waste volume by up to 90%, meaning there is still 1/10th of the mass left to bury in landfills. Additionally, due to simplistic design, the operations and maintenance cost per day is approximately 3% of capital cost per day (Tang 2012). Power produced via this method is less efficient than the other methods, achieving average results of 280 kwh per ton waste burned, and the resulting ash is not pure enough to merit recycling efforts (Tang 2012).

$$Capital\ Cost = \left(\frac{\$220{,}000}{ton\ waste}\right) * (W_{waste}) \qquad Eq.\ 13$$

$$Operation\ Cost(life) = \frac{Cost}{day} * 365 * availability * years \qquad Eq.\ 14$$

$$\frac{Cost}{day} = \frac{.03 * Capital\ Cost}{365 * availability} \qquad Eq.\ 15$$

$$Value(life) = \frac{Revenue}{day} * 365 * availability * years \qquad Eq.\ 16$$

$$\frac{Revenue}{day} = \left(E_{prod} * P_E\right) + \left(Fee_{tip} * W_{waste}\right) + \left(RECs * E_{prod}\right) \qquad Eq.\ 17$$

$$E_{prod} = (280\ kwh) * (W_{waste}) \qquad Eq.\ 18$$

Where E_{prod} is the energy produced (MWH), P_E is the price of energy $\left(\frac{\$}{MWH}\right)$, Fee_{tip} is the price per "tip" of a garbage truck $\left(\frac{\$}{ton}\right)$, W_{waste} is the weight of incoming waste (tons), and *RECs* are renewable energy credits given to renewable energy producers that have a value $\left(\frac{\$}{MWH}\right)$.

4. User Interface

The user interface is designed to keep the user focused solely on the first screen that comes up without a direct need to progress further down the spreadsheet unless supporting material is required. Figure 12 denotes the first screen the user can see when the spreadsheet is maximized. Within it is the User Input, Dashboard, and Graph sections that make it clear what is required of the user and gives the user the simple estimate requested.

Figure 12. User Dashboard.

Below the user dashboard is the non-editable section of the model, where the calculations happen. This section is important for when the user wants to understand where the numbers come from or when the model is updated. Figure 13 also shows the further references included for each model type to aid in the understanding of what exactly the user is calculating.

	A	B	C	D	E	F	G	H	I
25									
26	CELLS BELOW HERE ARE NOT USER MODIFIABLE								
27									
28	**Assumptions & Calculations**								
29									
30									
31	**Anaerobic Digestion**			**Plasma Gasification**			**Incineration**		
32									
33	Capital Cost	($55,159,416.90)	Current year dollars	Capital Cost	($89,500,000.00)	Current year dollars	Capital Cost	($66,000,000.00)	
34	Energy Produced	0.276	MWH	Energy Produced	159.9	MWH	Energy Produced	84	MWH
35	Digestate Produced	19.8	TPD	Slag Produced	52.5	TPD	Ash Produced	30	TPD
36	cost/day	($18,890.21)		cost/day	($28,847.70)		cost/day	($6,381.95)	
37	Revenue/day	$11,709.74		Revenue/day	$32,617.25		Revenue/day	$15,830.64	
38	Biogas Produced	115	m³ per day						
39									
40									
41	Assumptions:			Assumptions:			Assumptions:		
42	Minimum Input	34	tons/day	Minimum Input	100	tons/day	Minimum Input	10	tons/day
43	Availability	0.8		Availability	0.85		Availability	0.85	
44	Digestate Value	60.23	$/ton	Slag Value	228	$/ton	Ash Value	0	$/ton
45	REC	$1	$/MWH	REC	$1	$/MWH	REC	$1	$/MWH
46	Years to construct	4		Years to construct	4		Years to construct	4	
47	Tipping Fee	$35	$/ton	Tipping Fee	$35	$/ton	Tipping Fee	$35	$/ton
48	Shutdown Costs			Shutdown Costs			Shutdown Costs		
49	Reference	Anaerobic Digestion Costs		Reference	Plasma Gasification Costs		Reference	Incineration Costs	
50	Example Plant Cost	$8,563,428.57						Incineration Costs 2	
51	Example Plant CEPCI	100							
52	Biogas Conversion	32	m³ gas/m³ input						
53	Energy Conversion	21	MJ/m³ gas						
54	Type of Microbe	Thermophilic							

Figure 13. Dashboard Calculations.

Following the calculations is the generated graph data shown in Figure 14. Based on user input seen in Figure 12, the numbers automatically adjust the start and end dates. The price indices pull themselves from an internal table in eROI that is updated yearly.

	A	B	C	D	E	F	G	H	I
61	GRAPH DATA								
62		Active Digestion		Plasma Gasification		Incineration			
63	Year	Digestion	delta	Plasma	delta	Incineration	delta	Year	Price Index
64	0	-$13,789,854.23	-$13,789,854.23	-$22,375,000.00	-$22,375,000.00	-$16,500,000.00	-$16,500,000.00	2016	1.02
65	1	-$27,579,708.45	-$13,789,854.23	-$44,750,000.00	-$22,375,000.00	-$33,000,000.00	-$16,500,000.00	2017	1.04
66	2	-$41,369,562.68	-$13,789,854.23	-$67,125,000.00	-$22,375,000.00	-$49,500,000.00	-$16,500,000.00	2018	1.05
67	3	-$55,159,416.90	-$13,789,854.23	-$89,500,000.00	-$22,375,000.00	-$66,000,000.00	-$16,500,000.00	2019	1.05
68	4	-$57,256,113.86	-$2,096,696.96	-$88,296,099.80	$1,203,900.20	-$62,982,324.64	$3,017,675.36	2020	1.05
69	5	-$59,352,810.82	-$2,096,696.96	-$87,080,733.88	$1,215,365.92	-$59,935,909.52	$3,046,415.12	2021	1.06
70	6	-$61,449,507.78	-$2,096,696.96	-$85,853,902.24	$1,226,831.63	-$56,860,754.64	$3,075,154.89	2022	1.07
71	7	-$63,546,204.74	-$2,096,696.96	-$84,627,070.61	$1,226,831.63	-$53,785,599.75	$3,075,154.89	2023	1.07
72	8	-$65,642,901.70	-$2,096,696.96	-$83,388,773.26	$1,238,297.35	-$50,681,705.10	$3,103,894.65	2024	1.08
73	9	-$67,739,598.66	-$2,096,696.96	-$82,150,475.91	$1,238,297.35	-$47,577,810.45	$3,103,894.65	2025	1.08
74	10	-$69,836,295.62	-$2,096,696.96	-$80,900,712.84	$1,249,763.07	-$44,445,176.03	$3,132,634.42	2026	1.09
75	11	-$71,932,992.58	-$2,096,696.96	-$79,639,484.06	$1,261,228.78	-$41,283,801.85	$3,161,374.18	2027	1.1
76	12	-$74,029,689.54	-$2,096,696.96	-$78,366,789.56	$1,272,694.50	-$38,093,687.90	$3,190,113.95	2028	1.11
77	13	-$76,126,386.50	-$2,096,696.96	-$77,082,629.34	$1,284,160.22	-$34,874,834.19	$3,218,853.71	2029	1.12
78	14	-$78,223,083.46	-$2,096,696.96	-$75,798,469.13	$1,284,160.22	-$31,655,980.47	$3,218,853.71	2030	1.12
79	15	-$80,319,780.42	-$2,096,696.96	-$74,502,843.20	$1,295,625.93	-$28,408,387.00	$3,247,593.48	2031	1.13
80	16	-$82,416,477.38	-$2,096,696.96	-$73,195,751.55	$1,307,091.65	-$25,132,053.75	$3,276,333.24	2032	1.14
81	17	-$84,513,174.34	-$2,096,696.96	-$71,877,194.18	$1,318,557.36	-$21,826,980.74	$3,305,073.01	2033	1.15
82	18	-$86,609,871.30	-$2,096,696.96	-$70,535,705.39	$1,341,488.80	-$18,464,428.20	$3,362,552.54	2034	1.17
83	19	-$88,706,568.26	-$2,096,696.96	-$69,171,285.16	$1,364,420.23	-$15,044,396.13	$3,420,032.07	2035	1.19
84	20	-$90,803,265.22	-$2,096,696.96	-$67,772,467.78	$1,398,817.38	-$11,538,144.77	$3,506,251.37	2036	1.22
85	21	-$92,899,962.18	-$2,096,696.96	-$66,350,718.97	$1,421,748.81	-$7,974,413.87	$3,563,730.90	2037	1.24
86	22	-$94,996,659.14	-$2,096,696.96	-$64,894,573.01	$1,456,145.96	-$4,324,463.68	$3,649,950.19	2038	1.27
87	23	-$97,093,356.10	-$2,096,696.96	-$63,415,495.62	$1,479,077.39	-$617,033.96	$3,707,429.72	2039	1.29
88	24	-$99,190,053.06	-$2,096,696.96	-$61,913,486.80	$1,502,008.82	$3,147,875.30	$3,764,909.25	2040	1.31
89	25	-$101,286,750.02	-$2,096,696.96	-$60,400,012.26	$1,513,474.54	$6,941,524.32	$3,793,649.02	2041	1.32
90	26	-$103,383,446.98	-$2,096,696.96	-$58,863,606.28	$1,536,405.97	$10,792,652.87	$3,851,128.55	2042	1.34
91	27	-$105,480,143.94	-$2,096,696.96	-$57,315,734.60	$1,547,871.69	$14,672,521.18	$3,879,868.31	2043	1.35
92	28	-$107,576,840.90	-$2,096,696.96	-$55,767,862.91	$1,547,871.69	$18,552,389.50	$3,879,868.31	2044	1.35
93	29	-$109,673,537.86	-$2,096,696.96	-$54,219,991.22	$1,547,871.69	$22,432,257.81	$3,879,868.31	2045	1.35
94	30	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	2046	1.36
95	31	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	2047	1.37
96	32	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	2048	1.37
97	33	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	2049	1.38
98	34	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	2050	1.38
99	35	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	2051	1.39

Figure 14. Graph Calculations.

The plant cost calculation section, shown in Figure 15, is included for Plasma Gasification. This calculation must be conducted via the "most expensive equipment" method, since the direct cost of some of this equipment would have a much more profound effect and incur a base level cost than other estimation methods.

	A	B	C	D	E	F
100						
101						
102	Plant Cost Calculation					
103						
104	Plasma Gasification					
105	Name	Minimum per plant	Price			
106	Basic Plant Cost	1	$48,300,000.00			
107	Scalehouse	1	$500,000.00			
108	Utility interconnect	1	$1,500,000.00			
109	Waste pre-processing	1	$5,000,000.00			
110	Plasma Arc Furnace	1	$27,400,000.00			
111	Heat Exchanger	1	$6,800,000.00			
112						
113						
114			$89,500,000.00			
115						
116						

Figure 15. Plasma Gasification Cost.

In addition to the model, it was important to provide a user manual that ensured user input into the model was accurate.

5. Supporting Documentation

To make the additional module useful for a typical eROI user, supporting documentation was developed in the style of the eROI handbook that details similar specifics to this report, including how the numbers for each section are sequentially calculated and further reading for each WTE technology to achieve a proper understanding of the technology. A copy is included in the Appendix.

C. MODEL TESTING AND REFINEMENT

This model was developed solely from existing source data as stated above. As with any model, before inclusion into the eROI model it will be tested against real world data provided either by a DOD source or a researcher with appropriate authority to gather such information. When demonstrated for the sponsor, the model was accepted as a proof of concept for additional refinement. Further refinement will be as a result of type 3 and 4 testing, certification, and field performance data that allows users to directly update the model with the eROI team.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This research sought to improve the CNIC's eROI decision support tool through the development of an additional module that examines WTE technologies more thoroughly than the current model. Inclusion of this module provides a measure of a WTE project's maximum ROI in comparison with other technologies. It assists leaders throughout the Navy and DOD to make better-informed decisions with regard to energy and sustainability issues.

The major findings from this thesis support the premise that the feasibility of a location for WTE is testable with user-gathered data. These findings are supported by multiple sources outside of the DOD and agree with similar findings for commercial entities operating WTE facilities. Once a preliminary look has been conducted, a more thorough investigation of the best choice from this tool will provide accurate estimates of the value that the facility provides to the DOD.

The U.S. Navy has a variety of options for energy generation that do not rely on environmental factors. WTE technology has proven that it can provide a steady stream of power while also providing the benefit of reducing waste to landfill. Rigorous study of the formulas in the WTE module shows robustness to examine new conditions. The result is a way ahead for DON and DOD to test WTE technologies at different scales at specified locations.

There is no question that WTE technology has many positive benefits for its use. Creating energy and increasing the life of landfills by double or more can be a significant revenue stream to any user. The type of facility built will determine what it needs to be profitable. Building an analytical tool is only the first step in answering the sponsor's problem. It is important to the feasibility analysis that is integral to conceptual and preliminary design.

The crux of the research is in discovering and incorporating valid formulas for understanding WTE technologies. The resultant tool can predict the value of a WTE facility given inputs (waste) available at a military base. The user input data is simple and readily available for military sites.

B. RECOMMENDATIONS

Additional technologies for inclusion in the model or different methods of estimation are other areas that require continued research. Validation of the model against actual data is a necessary step to increase usage of the model.

Data should be gathered on several facilities in use within the United States. The data should be tested within the model and the errors graphed so that the error can be classified as systematic or random. If the error is within an acceptable range for the sponsor, then the module will fulfill its purpose and no modifications are needed. If the estimate falls outside of the sponsor's acceptable range, but are systematic, then the formulas will need a cost factor added. If the errors are randomly dispersed, then the model will need to be reworked to better fit the data.

There are additional cost factors that require further investigation, specifically the effect of plant shutdown costs and differences in tipping fees. Plant shutdown costs could help or harm the feasibility of a plant, depending if the equipment can be sold for profit or must be scrapped. This one-time scalable cost can be added into the spreadsheet via a cell already dedicated to the number. The eROI cost-benefit analysis includes some factors that affect the final number but are opinion based rather than calculated. The additional module developed does not adequately account for these cost factors, but they should be static values that always affect the outcome of each type of facility.

APPENDIX. WASTE TO ENERGY TAB, EROI MANUAL

This guide is to provide further information on the additional calculation tab for Waste-To-Energy (WTE) projects. This tab may be used to evaluate if further investigation is merited on an existing base for any of three types of WTE projects. As a brief background, this tab covers research done on Incineration, Anaerobic Digestion, and Plasma Gasification as methods of generating energy from traditional waste products.

A. INCINERATION

A waste incineration system raises trash to a high enough temperature to cause combustion, producing hot gas and ash. The ash has a largely reduced volume compared to the input, making it an efficient way to extend the life of a landfill. The ash can be used as a product in some industries or sold to the local community as a construction material so long as it is non-hazardous, and if those are not viable options it goes to the landfill (Environmental Services Association [ESA] 2016). Additionally, when the waste incinerated includes some metal products, some of the metal can be re-captured via recycling methods to be used as an additional source of revenue.

The gasses produced from combustion vary based on the trash that is burned, but a method of filtration for harmful products is required for this method. The gas can be run counter-current against the input trash, heating it up to reduce the required heat and residency time within the reactor. The gas can also be used to power a turbine-style engine, resulting in an energy product for the user.

In Figure 16, we see one example of this style of power plant. The incineration of trash can be environmentally harmful if not properly managed, as it results in effluent gasses that need to be scrubbed thoroughly to remove possible sulfur and nitrogen products that have negative impacts on the ozone and local air quality. According to AENews, the filters themselves then have to be disposed of as hazardous products or neutralized to make their storage acceptable (AENews 2016).

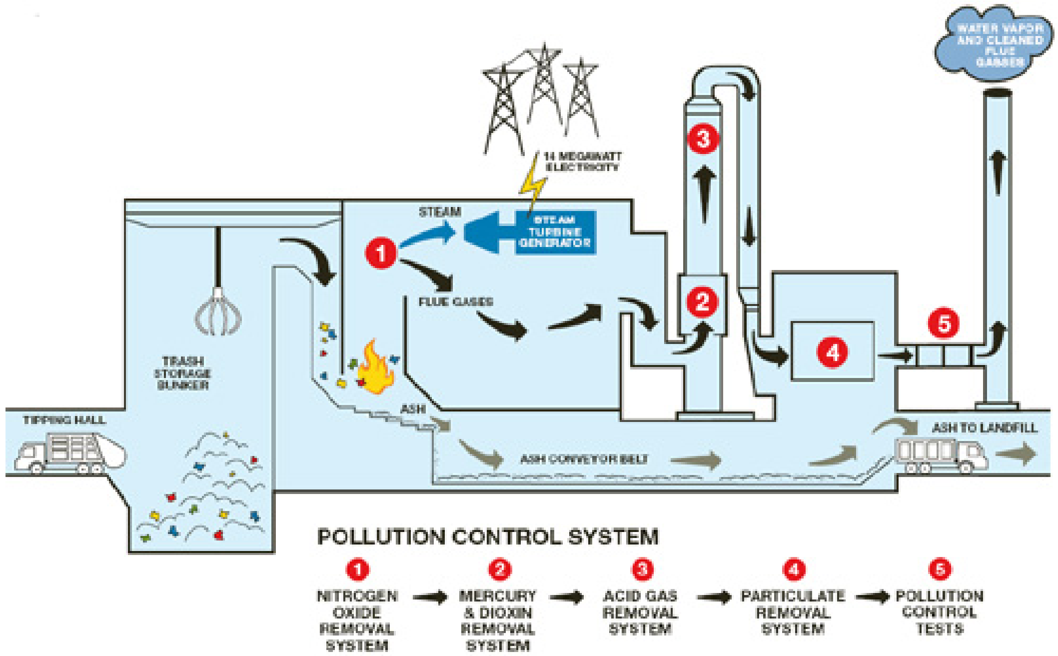


Figure 16. Incinerator with Cogeneration. Source: Taylor (2016).

B. ANAEROBIC DIGESTION

Anaerobic digestion uses a fermentation process to produce methane from organic waste inputs, resulting in a biogas that is then scrubbed (concentrated by removing contaminants) using a separation tower and either used directly as a product (biogas) or partially combusted to create higher-level hydrocarbons that can be used as fuels. Anaerobic digestion uses microbiomes that consume the waste and turn it into methane and carbon dioxide, the internal chemistry of the process described in Figure 17.

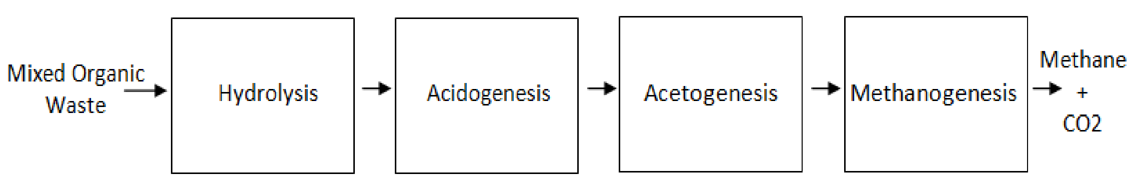


Figure 17. Digestion Process

The type of reaction tank and the environmental factors can greatly affect its efficiency of operation. However, it has a low energy input requirement for its conversion factor. An example of this style of WTE facility is shown in Figure 18.

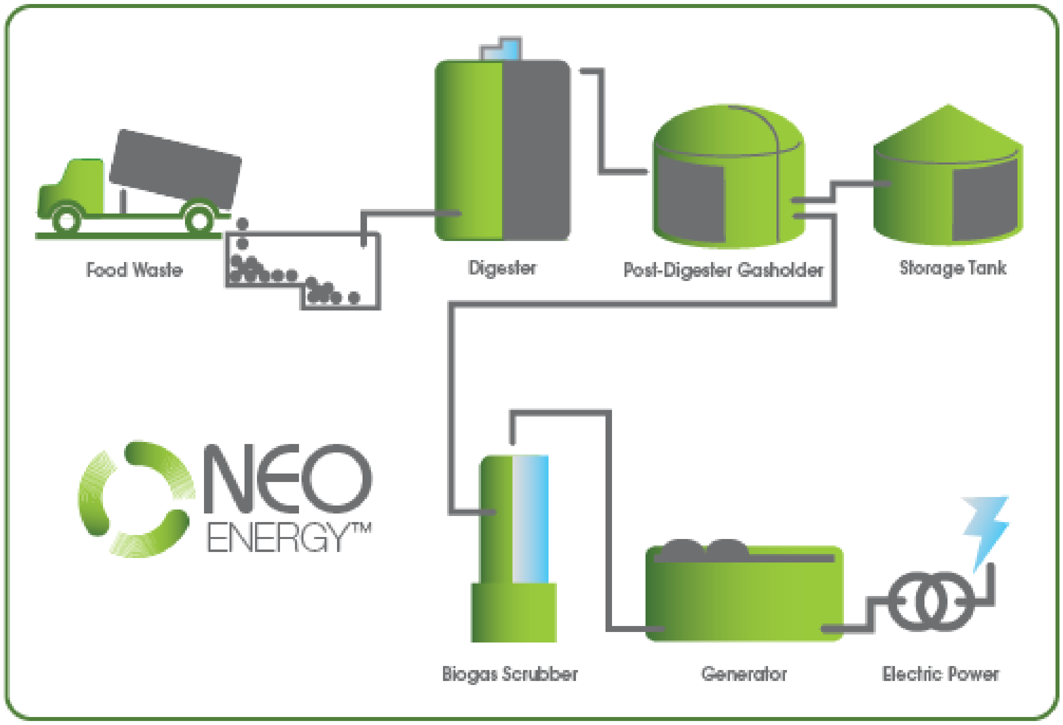


Figure 18. Anaerobic Digester Example. Source: NEO Energy (2016).

Anaerobic digestion is a mature technology, employed for energy production since the 1800s. Its effluent gas is used as an energy product, and its resulting "bottoms" (the solid product) can be used as an agricultural product or sent to a landfill as a reduced volume product. The process does not result in as large of a reduction in volume as incineration unless the bottoms are thereupon incinerated, and the plant produces a noticeable smell in the immediate vicinity of the plant. The chemistry of the reaction tank also requires monitoring and a significant input of water depending on the type of waste input so that the microbiomes continue to be active.

C. PLASMA GASIFICATION

Plasma gasification refers to the use of an arcing electrical current on organic materials. In the reaction chamber waste rises to a much higher temperature than possible by simple combustion, creating an efficiently converted effluent gas stream plus a small solid waste stream. This gas (largely hydrogen and hydrocarbons) can then be used as synthetic gas (syngas) in place of traditional methane and burned for use in a biogas engine or further refined and stored as a fuel source. An additional benefit is that the instantaneous conversion does not allow the formation of sulfur and nitrogen containing oxygen products (SO_X and NO_X) meaning that this method produces fewer gasses requiring filtration than incineration. The solid waste stream is a slag, inorganic compounds that could not be converted to syngas that can exceed 99% purity depending on what was input into the machine. They are completely stable and inert and can be used in construction products or separated for further processing as metal products (HowStuffWorks 2016). Figure 19 shows one example of a plasma gasification facility in the same style as some commercial facilities in Japan.

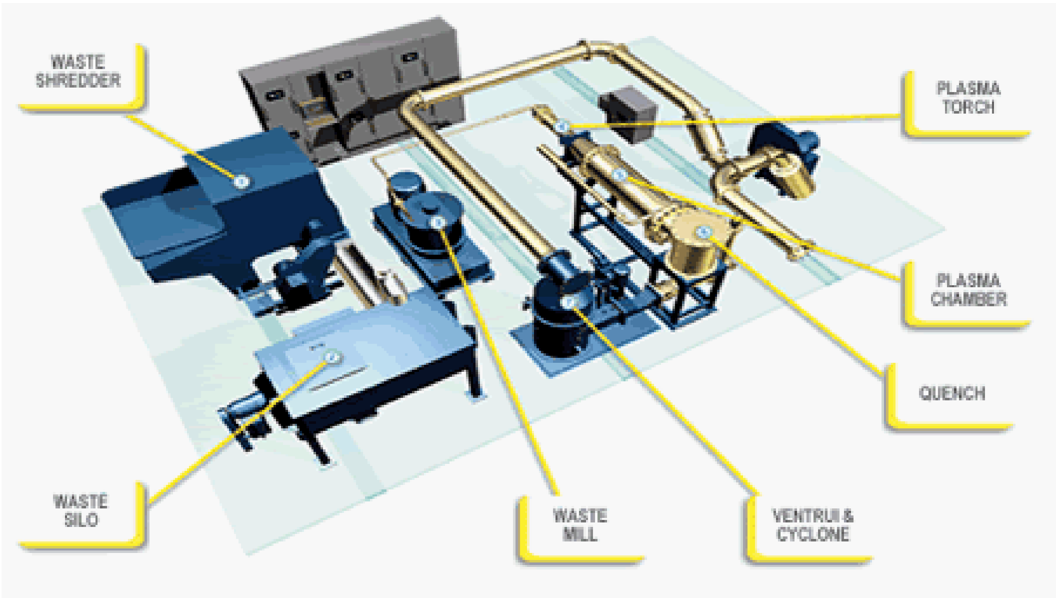
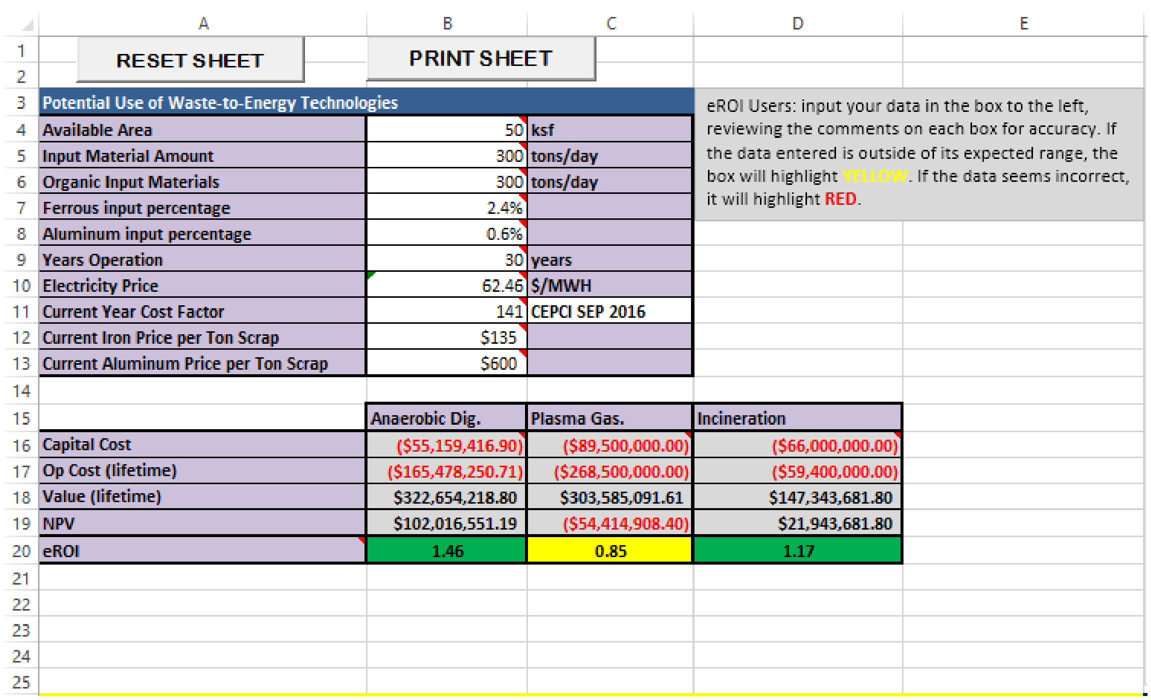


Figure 19. Plasma Gasification Process. Source: HowStuffWorks (2016).

Plasma gasification technology is the newest technology of these three choices, recently incorporated in the design for the Gerald R. Ford-class aircraft carrier (NEO Energy 2016). The disadvantages of this technology include the high initial cost, the risks associated with investing in a newer technology with complicated equipment, and a higher maintenance costs over alternatives.

D. USER DASHBOARD

Now that we understand what we are calculating estimates for with this tab, we will cover an overview of inputs and outputs provided by the user dashboard, shown in Figure 20. All user input will be in cells B4-B13 and C11. Each cell is coded with an explanation of what is required via an internal comment, and has suggested ranges and max/min values to let the user know they might be out of the boundaries that would make the project possible or feasible. Once all data is entered, the spreadsheet automatically will update cells B16:D20. Calculations are provided in the next section, and the research supporting these calculations is included via the resources at the end of this appendix.



	A	B	C	D
1	RESET SHEET	PRINT SHEET		
3	Potential Use of Waste-to-Energy Technologies			eROI Users: input your data in the box to the left, reviewing the comments on each box for accuracy. If the data entered is outside of its expected range, the box will highlight YELLOW. If the data seems incorrect, it will highlight RED.
4	Available Area	50	ksf	
5	Input Material Amount	300	tons/day	
6	Organic Input Materials	300	tons/day	
7	Ferrous input percentage	2.4%		
8	Aluminum input percentage	0.6%		
9	Years Operation	30	years	
10	Electricity Price	62.46	$/MWH	
11	Current Year Cost Factor	141	CEPCI SEP 2016	
12	Current Iron Price per Ton Scrap	$135		
13	Current Aluminum Price per Ton Scrap	$600		
15		Anaerobic Dig.	Plasma Gas.	Incineration
16	Capital Cost	($55,159,416.90)	($89,500,000.00)	($66,000,000.00)
17	Op Cost (lifetime)	($165,478,250.71)	($268,500,000.00)	($59,400,000.00)
18	Value (lifetime)	$322,654,218.80	$303,585,091.61	$147,343,681.80
19	NPV	$102,016,551.19	($54,414,908.40)	$21,943,681.80
20	eROI	1.46	0.85	1.17

Figure 20. User Input Dashboard

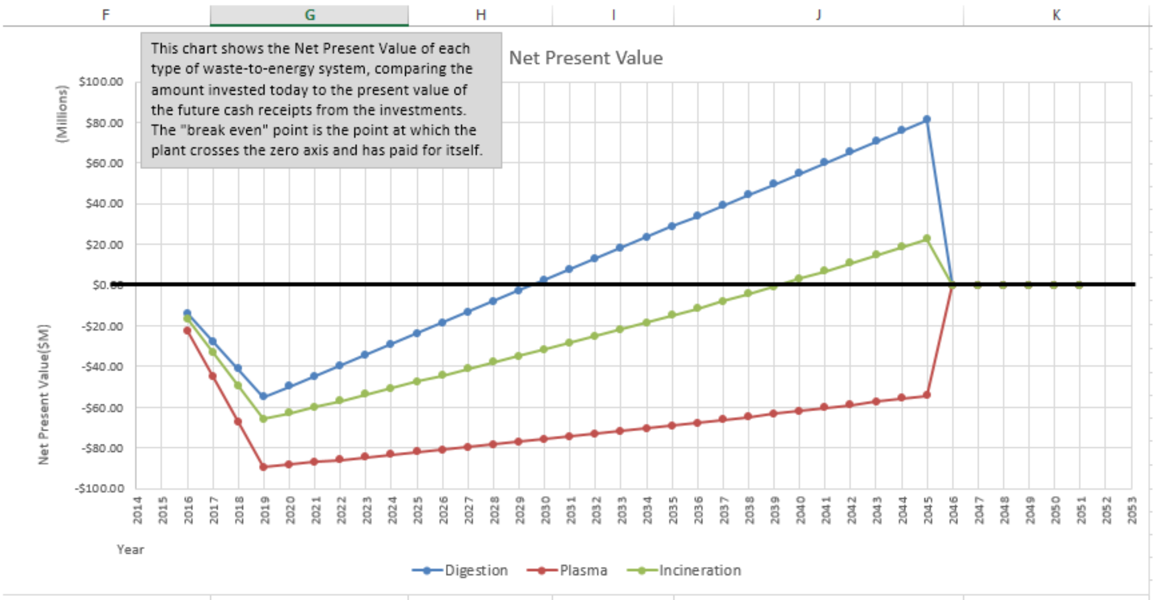


Figure 21. Net Present Value Chart

E. CALCULATIONS

1. Anaerobic Digestion Calculations

For Anaerobic Digestion, the seven-tenths rule from Perry's (Perry 2008) and the sample study from *Biocycle* (GRN 2016) magazine were used. A plant estimated at 34 tons/day processing power and a CEPCI of 100 was valued at $8.5 million. The capital cost formula was then applied using the ratio of user input tons/day of material versus the sample plant and then adjusted via the current CEPCI. Costs per year were assumed at 10% of the capital costs (Perry 2008). The revenue is a summation of the digestate and electricity produced, both of which are dependent on the percentage of organic materials that comprise the input waste. The digestate can be reasonably estimated to have a value of $60 per ton. Methane content of biogas can vary, but normally comprises approximately 55% by volume of the resultant gas. This lower methane content results in the biogas producing energy at approximately 6 kwh per cubic meter of methane, with expected engine efficiency of .4 when using combined heat and power engines (Perry 2008).

$$Capital\ Cost = Example\ Plant\ Cost * \left(\frac{Est.Capacity}{Example\ capacity}\right)^{.7} * \left(\frac{CEPCI_{current}}{CEPCI_{example}}\right) \quad Eq.\ 1$$

$$Operation\ Cost(life) = \frac{Cost}{day} * 365 * availability * years \quad Eq.\ 2$$

$$\frac{Cost}{day} = \frac{.1 * Capital\ Cost}{365 * availability} \quad Eq.\ 3$$

$$Value(life) = \frac{Revenue}{day} * 365 * availability * years \quad Eq.\ 4$$

$$\frac{Revenue}{day} = (E_{prod} * P_E) + (Digest_{prod} * P_D) + (Fee_{tip} * W_{waste}) + (RECs * E_{prod}) \quad Eq.\ 5$$

$$E_{prod} = [(115 * Wt\%_{Organic}) + (95 * Wt\%_{Inorganic})] m^3 biogas * \frac{(6 * 10^{-3}\ MWH)}{m^3 biogas} \quad Eq.\ 6$$

where E_{prod} is the energy produced (MWH), P_E is the price of energy $\left(\frac{\$}{MWH}\right)$, $Digest_{prod}$ is the amount of digestate produced $\left(\frac{tons}{day}\right)$, P_D is the price of the digestate $\left(\frac{\$}{ton}\right)$, Fee_{tip} is the price per "tip" of a garbage truck $\left(\frac{\$}{ton}\right)$, W_{waste} is the weight of incoming waste (tons), and *RECs* are renewable energy credits given to renewable energy producers that have a value $\left(\frac{\$}{MWH}\right)$.

2. Plasma Gasification Calculations

Plasma gasification will take input waste of any mixture and turn it into Syngas, a flammable mixture of methane and other combustible gasses typically burned for electricity, and slag, a mixture of ash and inorganic materials that are processed to obtain purified components or landfilled. Estimation via equipment scale-up was conducted to calculate the capital cost of the plant. The tons per day of input waste was multiplied by $220,000, the average dollar cost per ton for a basic mass-burn plant equipment setup. This number was then scaled back by 25% to account for equipment that is covered by specific large pieces of equipment for estimation purposes (Clark 2016). Other basic equipment costs are added, including the scale house cost (where the waste enters the plant), the utility interconnections cost, the waste pre-processing (where the waste is shredded as much as possible), the plasma arc furnace itself, and the heat exchanger that keeps the reaction vessel, where the conversion happens, at an appropriate temperature. All of this produces a total capital cost, which is adjusted to current year dollars.

The energy produced is estimated at 533 kW per ton of waste input, though the actual amount will vary, largely based on the types of input waste and other factors. Table 2 shows that slag can be reasonably estimated at 350 lbs. per ton processed, and that the slag can be valued at approximately the price of the metals contained therein, $228 per ton processed. Additional revenue comes from the local tipping fee (averaged at $35/ton, entirely location dependent) and Renewable Energy Credits from the government (volatile market, very low estimate of $1/MWH produced via renewable sources).

The Operation and Maintenance cost of a plasma gasification plant can be estimated to be approximately 10% of its capital cost per year based on the model presented in the NAWTEC article (Clark 2016).

$$Capital\ Cost = \left[\left(\frac{\$220{,}000}{ton\ waste}\right) * (W_{waste}) * .75 - \$1{,}200{,}000\right] + Cost_{equipment} \qquad \textit{Eq. 7}$$

$$Operation\ Cost(life) = \frac{Cost}{day} * 365 * availability * years \qquad \textit{Eq. 8}$$

$$\frac{Cost}{day} = \frac{.1 * Capital\ Cost}{365 * availability} \qquad \textit{Eq. 9}$$

$$Value(life) = \frac{Revenue}{day} * 365 * availability * years \qquad \textit{Eq. 10}$$

$$\frac{Revenue}{day} = \left(E_{prod} * P_E\right) + \left(Slag_{prod} * P_S\right) + \left(Fee_{tip} * W_{waste}\right) + \left(RECs * E_{prod}\right) \textit{Eq. 11}$$

$$E_{prod} = \frac{533\ kwh}{ton\ waste} * W_{waste} \qquad \textit{Eq. 12}$$

where E_{prod} is the energy produced (MWH), P_E is the price of energy $\left(\frac{\$}{MWH}\right)$, $Slag_{prod}$ is the amount of slag produced $\left(\frac{tons}{day}\right)$, P_S is the price of the slag $\left(\frac{\$}{ton}\right)$, Fee_{tip} is the price per "tip" of a garbage truck $\left(\frac{\$}{ton}\right)$, W_{waste} is the weight of incoming waste (tons), and *RECs* are renewable energy credits given to renewable energy producers that have a value $\left(\frac{\$}{MWH}\right)$.

3. Incinerator Calculations

Incinerators are some of the oldest and most basic WTE technology, and as such are well understood for cost estimation purposes. A standard mass-energy burn plant can be estimated at $220,000 times the input tons per day for capital costs (Clark 2016). Additionally, taking into consideration losses due to efficiency and parasitic electricity costs the average amount of electricity produced is 200 KWH per ton of waste burned daily. The process reduces waste volume by up to 90%, meaning there is still 1/10th of the mass left to bury in landfills. Additionally, due to simplistic design, the operations and maintenance cost per day is approximately 3% of capital cost per day (Tang 2012). Power produced via this method is less efficient than the other methods, achieving average results of 280 kwh per ton waste burned, and the resulting ash is not pure enough to merit recycling efforts (Tang 2012).

$$Capital\ Cost = \left(\frac{\$220{,}000}{ton\ waste}\right) * (W_{waste}) \qquad Eq.\ 13$$

$$Operation\ Cost(life) = \frac{Cost}{day} * 365 * availability * years \qquad Eq.\ 14$$

$$\frac{Cost}{day} = \frac{.03 * Capital\ Cost}{365 * availability} \qquad Eq.\ 15$$

$$Value(life) = \frac{Revenue}{day} * 365 * availability * years \qquad Eq.\ 16$$

$$\frac{Revenue}{day} = \left(E_{prod} * P_E\right) + \left(Fee_{tip} * W_{waste}\right) + \left(RECs * E_{prod}\right) \qquad Eq.\ 17$$

$$E_{prod} = (280\ kwh) * (W_{waste}) \qquad Eq.\ 18$$

where E_{prod} is the energy produced (MWH), P_E is the price of energy $\left(\frac{\$}{MWH}\right)$, Fee_{tip} is the price per “tip” of a garbage truck $\left(\frac{\$}{ton}\right)$, W_{waste} is the weight of incoming waste (tons), and *RECs* are renewable energy credits given to renewable energy producers that have a value $\left(\frac{\$}{MWH}\right)$.

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LIST OF REFERENCES

AENews. 2016. "Negative Impacts of Incineration-based Waste-to-Energy Technology." Last modified May 01. http://www.alternative-energy-news.info/negative-impacts-waste-to-energy/.

Athanasiou, C., D. Tsalkidis, E. Kalogirou, and E. Voudrias. 2015. "Feasibility Analysis of Municipal Solid Waste Mass Burning in the Region of East Macedonia—Thrace in Greece." *Waste Management & Research* 33, no. 6: 561–69. doi:10.1177/0734242x15587368.

Brown, Jim. 2015. *Web EROI Project Development User Manual*. CNIC Navy Shore Energy Program Development.

Clark, Bruce J., and Marc J. Rogoff. 2010. "Economic Feasibility of a Plasma ARC Gasification Plant , City of Marion, Iowa." In *Proceedings of the 18th Annual North American Waste-to-Energy Conference*. doi: 10.1115/*NAWTEC18-3502*.

E-Education Institute. 2016. "Incineration Example." Last modified May 11. https://www.e-education.psu.edu/egee110/sites/www.education.psu.edu.egee110/files/lesson09/waste_energy_plant_diagram.jpg.

EIA. 2016. "How Much U.S. Energy Consumption and Electricity Generation Comes from Renewable Energy Sources?" EIA FAQ. Last modified April 04. https://www.eia.gov/tools/faqs/faq.cfm?id=92&t=4.

Environmental Services Association. 2016. "Energy from Waste." Last modified May 01. http://www.esauk.org/energy_recovery/iba_-_incinerator_bottom_ash.html.

The Gasification and Syngas Technologies Council. 2016. Last modified May 01. http://www.gasification-syngas.org/.

Global Recycling Network. 2016. "Enviros RIS in Global Recycling Network." Last modified August 01. http://www.grn.com/equip/aa022839.html.

HowStuffWorks. 2016. "How Plasma Converters Work." Last modified April 01. http://science.howstuffworks.com/environmental/energy/plasma-converter.htm.

Moore, Mary K., and Elmer B. Ledesma. 2014. *Academia and Industrial Pilot Plant Operations and Safety*. Washington, DC: American Chemical Society.

Neo Energy. 2016. "The Anaerobic Digestion Process—NEO Energy." Last modified May 01. http://www.neoenergyusa.com/biogas-process/.

New Energy and Fuel. 2016. “Pyrolysis Oil Gets More Practical Refining.” Last modified May 01. http://newenergyandfuel.com/http:/newenergyandfuel/com/2010/12/03/pyrolysis-oil-gets-more-practical-refining/.

Perry, Robert H., and Don W. Green. 2008. *Perry’s Chemical Engineers’ Handbook*. New York: McGraw-Hill.

Tang, Jiao. 2012. “A Cost-Benefit Analysis of Waste Incineration with Advanced Bottom Ash Separation Technology for a Chinese Municipality—Guanghan.” Master’s thesis, Vienna School of International Studies.

Whyte, Rob, and Guy Perry. 2001.”A Rough Guide To Anaerobic Digestion Costs And MSW Diversion.” October 2001. http://infohouse.p2ric.org/ref/44/43217.pdf.

Wold, Barbara. 2010. “Democracy for New Mexico.” Democracy for New Mexico: Green Economy. Last modified May 11. http://www.democracyfornewmexico.com/democracy_for_new_mexico/green_economy/page/6/.

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